Modeling and optimization of content-oriented and survivable optical networks

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Agenda

• Motivation
• Research area
  – Network flows
  – Optical networks
  – Routing problems
  – Survivability provisioning
• Recent works
  – Modeling and optimization approaches
  – Realistic case study
• Future works
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First Wide Area Network

ARPANET 1970

San Francisco
- SRI
- STANFORD
- UCSB
- SDC
- RAND

Los Angeles
- UCLA

Greater Boston
- MIT
- HARVARD
- BBN
- LINCOLN
- CARNEGIE
- CASE

Utah
Increase of the network traffic

Source:
Increase of the network traffic

Global IP traffic will increase nearly 3-fold over the next 5 years, and will have increased 127-fold from 2005 to 2021.

Source:
Increase of the network traffic: example services

Source:
Increase of the network traffic: example services

It would take an individual more than 5 million years to watch the amount of video that will cross global IP networks each month in 2021.

Source:
Increase of the network traffic: data center traffic

Source:
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• Future works
Unicast (one-to-one)
Anycast (one-to-one of many)
Multicast (one-to-many)
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Evolution of optical networks (1)

1. Single-Line-Rate (SLR) DWDM
   - Use of a single-carrier modulation format (such as NRZ) with a single bit rate (10Gb/s) in the entire network and with the fixed DWDM frequency grid
     - low Spectral Efficiency (SE)
     - costly (several transponders for large demands)

2. Mixed-Line-Rate (MLR) DWDM
   - Introduction of different advanced modulation formats (m-PSK, m-QAM) in the same network
     + improved SE (due to the use of higher modulation levels on shorter paths)
     + 100 Gb/s connection provisioning

3.a) Elastic Optical Network (EON) with single-carrier modulation
   - Introduction of flexible frequency grids and Bandwidth Variable Wavelength Selective Switches (BV-WSS)
     + improved SE (due to the flexible spectrum allocation)
     + 100+ Gb/s connection provisioning

3.b) Elastic Optical Network (EON) with multi-carrier transmission (such as Optical OFDM)
   - Introduction of Bandwidth Variable Transponders (BV-T)
     + elastic bandwidth provisioning by allocating a number of Sub-Carriers
     + improved SE (thanks to O-OFDM)
Elastic Optical Network (EON)

Fiber contains $S$ spectral slots (slices) in flexible grid
Space Division Multiplexing (SDM)

Fiber contains $k$ spatial resources and $S$ spectral slots (slices) in flexible grid
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Routing and Spectrum Allocation: unicast

<table>
<thead>
<tr>
<th>DEMAND</th>
<th>ROUTE</th>
<th>SLICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNI</td>
<td>0→2</td>
<td>4</td>
</tr>
</tbody>
</table>

Slices: 1-4

Nodes:
- Node 0
- Node 1
- Node 2
- Node 3
- Node 4
Routing and Spectrum Allocation: anycast

<table>
<thead>
<tr>
<th>DEMAND</th>
<th>ROUTE</th>
<th>SLICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANY</td>
<td>1→R</td>
<td>4</td>
</tr>
</tbody>
</table>

Data center

Node 0

Node 1

Node 2

Node 3

Node 4

Slices: 1-4
Routing and Spectrum Allocation: multicast

<table>
<thead>
<tr>
<th>DEMAND</th>
<th>ROUTE</th>
<th>SLICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULTI</td>
<td>0→1,3,4</td>
<td>4</td>
</tr>
</tbody>
</table>
Distance-Adaptive Transmission

Path length: 1000 km

Path length: 2000 km

<table>
<thead>
<tr>
<th></th>
<th>BPSK</th>
<th>QPSK</th>
<th>8QAM</th>
<th>16QAM</th>
<th>32QAM</th>
<th>64QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum [GHz]</td>
<td>50</td>
<td>25</td>
<td>16.67</td>
<td>12.5</td>
<td>10</td>
<td>8.33</td>
</tr>
<tr>
<td>Frequency slices</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Regenerators path 1000 km</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Regenerators path 2000 km</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
Cost and energy consumption

Cost of:
- Spectrum resources
- Transponders (BV-T)
- Regenerators (REG)

Energy consumption of:
- Transponders
- Regenerators
Spectrum usage

Maximum

\[ z_{\text{max}} = \max_i e_i = 8 \]

Average:

\[ z_{\text{av}} = \frac{1}{|E|} \sum_i e_i = 4.33 \]
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Path-based survivability: protection and restoration

<table>
<thead>
<tr>
<th>DEMAND</th>
<th>ROUTE</th>
<th>VOLUME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uni</td>
<td>0→2</td>
<td>60 GBPS</td>
</tr>
</tbody>
</table>

- Disjoint paths
- Different modulations
- Channel assignment policies
- Sharing spectrum
- Amount of data to be protected
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Optimization methods

- ILP models (exact method)
- Column generation technique
- Greedy algorithms
- Metaheuristic approaches
ILP modeling

Comparison of different ILP models of the same problem:

– Channel-based (CB)
– Slice-based (SB)


CB: spectrum usage modeling

![Diagram showing spectrum usage with various bands labeled C1 to C9, each with a value of n=2, n=4, or n=6, and time slots S1 to S6.](image-url)
CB: spectrum usage modeling

\[ C_1 = \{ \text{first slice index, last slice index, number of slices} \} \]

For each traffic demand \( d \) saves:

\[ x_{dpc} \]

Information about selected routing structure \( p \) and frequency channel \( c \) allocated on this structure
SB: spectrum usage modeling

For each traffic demand \( d \) saves:

\[ x_{dp} \]  Information about selected routing structure

\[ w_d \]  index of the first allocated slice

\[ z_d \]  index of the last allocated slice
Column Generation (CG)-based methods

• Column generation is a decomposition method
• Efficient solution approach for problems with a high number of variables

Greedy and metaheuristic approaches

• Adaptive Frequency Assignment (AFA) – dedicated greedy method [9]
• Tabu Search [9], [10]
• Swarm intelligence [11], [12]


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Design of content-oriented and survivable network

<table>
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<tr>
<th>DEMAND</th>
<th>ROUTE</th>
<th>VOLUME</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANY</td>
<td>1→DC</td>
<td>100 GB/s</td>
</tr>
<tr>
<td>ANY</td>
<td>3→DC</td>
<td>350 GB/s</td>
</tr>
<tr>
<td>UNI</td>
<td>2→4</td>
<td>200 GB/s</td>
</tr>
</tbody>
</table>

Joint problem

Two subproblems

DC location and routing

1. DC location
2. Routing

Benefits of anycasting in EONs

Benefits of multicasting in EONs

Comparison of protection methods in optical networks


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Main research interest

- Content-oriented, DC-oriented networks
- Optical transmission
- Survivability provisioning
- Modeling and optimization approaches
- Realistic case studies
Optimization methods based on machine learning

<table>
<thead>
<tr>
<th>Demand</th>
<th>Route</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANY</td>
<td>2 → DC</td>
<td>200 GB/s</td>
</tr>
<tr>
<td>ANY</td>
<td>3 → DC</td>
<td>360 GB/s</td>
</tr>
<tr>
<td>UNI</td>
<td>4 → 0</td>
<td>150 GB/s</td>
</tr>
<tr>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Traffic prediction
Protection against electromagnetic attacks

• Weapon of mass destruction: explosion and following electromagnetic pulse (EMP)
Protection against electromagnetic attacks

- High-power microwave (HPM)

Thank you for attention

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